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A Comparison of Visual and Measurement-Based Techniques for Quantifying Cobble Embeddedness and Fine-Sediment Levels in Salmonid-Bearing Streams

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Abstract.—Excess fine-sediment loading can strongly affect the performance of salmonids rearing in fluvial habitats. Consequently, there are multiple techniques for quantifying the biologically relevant aspects of streambed material quality. While similar methods should provide similar measurements for a given attribute, little information is available that validates this assumption. Nevertheless, there are ongoing efforts toward assembling and analyzing large-scale habitat databases using existing information collected via multiple techniques. For these reasons, we used regression to compare visual and measurement-based approaches for two commonly assessed substrate variables (cobble embeddedness and percent surface fines). For both embeddedness and percent fines, we found moderate to strong linear relationships (R^2 = 0.46–0.83) between estimates obtained by visual and measurement-based approaches. However, the fitted line differed significantly from a null 1:1 expectation for the percent fines and embeddedness analyses, indicating that there is a differential bias between visual and measurement-based techniques relative to the true, but unknown, value. The observed deviation between embeddedness methods, which is primarily due to differences in measurement strategy, is probably of considerable practical significance. Conversely, the difference between techniques for percent fines appears to be negligible considering published information on observer variability for this attribute. In summary, our study provides a means for understanding and accounting for differences in substrate methods of direct relevance to large-scale habitat assessment efforts.

Anthropogenic activities can influence the magnitude and timing of sediment delivery to rivers flowing through managed landscapes. Soil erosion from logging, livestock grazing, mining, and road construction activities has increased sediment loading and deposition in streams throughout North America (Meehan 1991), often producing levels much greater than those considered natural (Platts et al. 1989). This form of habitat degradation has adverse consequences for many aquatic organisms, and effects of fine sediments have been particularly well documented for salmonid fishes, many of which are endangered, threatened, or of special concern (Young 1995).

The negative effects of excess fine sediments have been evaluated experimentally for several salmonid species and are pronounced for the embryonic and juvenile life stages (Bjornn et al. 1977; Chapman 1988). In suspension, fine sediments can cause high turbidity and impede the ability of fish to acquire food and grow (Sigler et al. 1984; Lloyd 1987). Upon deposition, an increasing fraction of fine sediments within spawning gravels reduces egg incubation survival (particles < 1 mm) and impairs the ability of fry to emerge from redds (particles < 10 mm; see Chapman 1988 and Kondolf 2000 for reviews). Further, high sedimentation can limit the availability of free interstitial spaces among cobble substrates and can thereby reduce juvenile growth, survival, and overall rearing capacity in impacted habitats (Bjornn et al. 1977; Hillman et al. 1987; Suttle et al. 2004). Given these effects, many plans currently emphasize habitat restoration as a means for recovering imperiled fish populations occupying degraded streams (Larsen et al. 2004).

To identify candidate streams for habitat restoration and monitor subsequent effects, reliable approaches are greatly needed for quantifying biologically relevant characteristics of stream substrate quality. Toward this end, there are several techniques for quantifying any given substrate parameter, ranging from rapid visual estimation methods to more time-intensive, measurement-based approaches (Bain and Stevenson 1999; Bain et al. 1999). However, this range of options, coupled with project-specific data needs, has led to some inconsistency in where and when different techniques have been applied (Bain et al. 1999). Further, although the more time-intensive, measurement-based methods are considered superior (Kondolf 2000; Whitman et al. 2003), limited bud-

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gets often force biologists to employ the more rapid visual methods during surveys. While it is believed that both approaches yield comparable values for a given attribute, this assumption has not been validated for even the most commonly assessed parameters (but see Wang et al. 1996). Based on this lack of validation, the reliability of habitat databases collated from preexisting multiagency, multitechnique surveys is unknown (Bauer and Ralph 2001); this may limit the utility of such information in evaluating restoration potential or prioritizing efforts at large scales (e.g., as is currently being done for Chinook salmon *Oncorhynchus tshawytscha* in the Columbia River basin; Mobrand et al. 1997; McHugh et al. 2004).

In this paper, we provide an evaluation of the quantitative relationships between visual and measurement-based approaches for quantifying two substrate attributes that are commonly assessed in salmonid stream habitat surveys. Our first objective was to compare a visual estimation method for cobble embeddedness (i.e., ''the degree to which fine sediments surround coarse substrates on the surface of a streambed''; Sylte and Fischenich 2002) with an objective, measurement-based technique designed to assess the same substrate parameter. As a second objective, we compared values for the percent of area within pools covered by fine sediments (<10 mm; hereafter referred to as percent fines) obtained using two methods: (1) a visual estimation method (Bain and Stevenson 1999) and (2) the Wolman pebble count method (Wolman 1954). Thus, our overall focus was on determining whether expedient visual methods and measurement-based techniques yield similar results when applied simultaneously; other aspects of habitat assessment (e.g., sample design and observer effects), though important, were not considered in the present study.

Methods

Cobble embeddedness.—For our first objective, we measured and visually estimated cobble embeddedness in four northeastern Oregon streams (Lick Creek and the Minam, Imnaha, and Grande Ronde rivers) and two central Idaho streams (Elk and Sulphur creeks) during the summers of 2001 and 2002. These sites were selected and surveyed as part of a larger study on Chinook salmon habitat restoration potential and therefore encompassed a wide range of habitat conditions (degraded to pristine), stream sizes (base flow range = 0.43–5.56 m^3/s), and gross geologies (intrusive igneous and mixed lithology classes). For a detailed description of habitat attributes and land use conditions in these streams, see McHugh et al. (2004). In each stream, embeddedness data were collected within the context of a 10% systematic sample of all pools and riffles (i.e., based on Hankin and Reeves' [1988] survey approach) occurring within reaches where biologists monitor annual trends in spawning salmon abundance (reach length range = 7.4–29.5 km).

Within each sampled pool or riffle, we used two methods in sequence to quantify embeddedness within a single, randomly located (via a blind toss), 60-cm-diameter steel hoop. First, based on the judgment of trained observers, the area within the hoop was classified into one of five embeddedness categories (Platts et al. 1983); the categories were numerical classes ranging from 1 to 5, corresponding to the embeddedness levels of over 75, 50–75, 25–50, 5–25, and less than 5%, respectively. In total, this procedure takes 30 s or less to perform (in a 60-cm-diameter hoop). After the visual assessment, we then quantified embeddedness in the same area by means of the hoop method of Burns (unpublished report to U.S. Forest Service, Payette National Forest, 1984) and Skille and King (unpublished report to the Idaho Department of Environmental Quality, 1989). This method relies on the measurement of two attributes of cobbles embedded within the fine-sediment framework encompassed by the 60-cm hoop: (1) the embedded height (D_e), or the vertical height of the particle that was embedded in fines prior to removal; and (2) the total vertical height of the particle (D_t). We made both measurements with a ruled Plexiglas frame while holding each particle in its original spatial orientation (i.e., as it was found upon removal from the streambed). Ultimately, these measurements were used to calculate embeddedness as $[(\Sigma D_e)/(\Sigma D_t)] \cdot 100$, which was also weighted if surface fines occupied more than 10% of the hoop area (see Sylte and Fischenich 2002 for a review of embeddedness protocols). In contrast to the visual approach, a measurement-based assessment of cobble embeddedness within a 60-cm hoop takes approximately 5 min to complete.

In total, we assessed embeddedness visually and using the hoop method within 154 hoops (Lick Creek: n = 32; Minam River: n = 12; Imnaha River: n = 12; Grande Ronde River: n = 21; Elk Creek: n = 45; Sulphur Creek: n = 32); observations were made by a total of five different experienced technicians. While Sylte (2002) reports that interobserver effects (e.g., varying judgment in visual ratings) can account for a significant portion of variance in embeddedness data, we do not consider this aspect of habitat assessment in our study because (1) the majority (84%) of the 154 observations were made by only two technicians (observer 1 [McHugh]: 55%; observer 2: 29%; observers 3–5: 16%); (2) the lead author trained all observers extensively on substrate methods prior to data collection; and (3) a preliminary analysis of covariance (response: hoop value; main effects: visual value [covariate], observer) demonstrated that less than 2% of the variation in measured embeddedness was due to observer effects (observer effect: $F_{4,153} = 1.27$, $P = 0.2834$, partial $R^2 = 0.018$).

Percent fines.—During the summer of 2003, we quantified the percent of surface area occupied by fine sediments (<10 mm; Kondolf 2000) within 18 in situ experimental pools constructed in the Logan River, Utah. Experimental pools consisted of an approximately 20-m^2 (3.3 × 6.0 m) area enclosed with screen and T-posts (with an open bottom) and were built for use in an experiment on trout interactions; thus, substrate characteristics within pools were natural and representative of fluvial environments. Physical habitat conditions varied considerably across the sites at which we assessed percent fines (e.g., base flow range: 0.45–2.69 m^3/s; de la Hoz Franco and Budy 2005).

As in our embeddedness assessment, we used both a visual approach (Bain and Stevenson 1999) and a measurement-based technique (the Wolman pebble count; Wolman 1954) to determine percent fines. Under the visual approach, we determined sediment size at a minimum of five points equally spaced along each of five transects (perpendicular to flow) systematically arrayed along the length of a single experimental pool. We used a modified version of the Wentworth scale (Bain and Stevenson 1999) to estimate the dominant particle size (i.e., occupying the majority of area) within an approximately 1-m^2 area surrounding the sample point. Thus, the particle size-classes based on our modification were boulder (>256 mm), cobble (64–256 mm), pebble (16–63 mm), gravel (10–15 mm), and fines (<10 mm). Based on these size-classes, we estimated the percent of the total pool area occupied by surface fines. On average, this procedure takes 3–4 min to complete. In the same pool, we then assessed percent fines with the measurement-based Wolman pebble count technique (Wolman 1954). Using a hand ruler, we measured the intermediate axis (*b*-axis) of at least 25 blindly selected particles from each of four to five transects that spanned the wetted width of the pool (perpendicular to flow). Using these data, we computed percent fines as the fraction of particles smaller than 10 mm in diameter. For a comparison to the visual approach, it takes 7–8 min to complete a measurement-based assessment of percent fines. Because percent fines data were collected by a single observer only (McHugh), interobserver variability was nonexistent for this attribute and is thus not considered in subsequent analyses.

As a final note on fine-sediment methods, we defined fines as those particles less than 10 mm in diameter based on a combination of biological and practical considerations. With respect to biological considerations first, Kondolf (2000) recommended use of a 10-mm criterion when considering the effects of sedimentation on salmonid fry emergence success. Secondly, although defining fines based on a smaller criterion (e.g., <1 mm) may be desirable, 4 mm is the smallest particle that could we could effectively measure with a ruler during pebble counts. Further, the choice of criterion (≤4-mm or <10-mm) does not affect our analysis, as percent fines values estimated by these two criteria are nearly perfectly correlated (Pearson's correlation coefficient: $R = 0.996$).

Statistical analysis.—For both cobble embeddedness and percent fines analyses, we used a simple linear regression framework to evaluate the assumption that visual and measurement-based techniques yield similar results. We regressed the measurement-based value (*y*-variable) against the visually estimated value (*x*-variable) and used an *F*-test to test the simultaneous null hypothesis of a slope (β_1) of one and an intercept (β_0) of zero. In cases where this simultaneous null hypothesis was rejected, we evaluated slope and intercept hypotheses separately in order to understand the source of deviation between methods (i.e., whether the deviation was due to deviation in the slope, intercept, or both). We completed these analyses by use of PROC REG in the Statistical Analysis System (SAS Institute 2002) and assessed statistical significance at an α level of 0.05.

Results

Cobble Embeddedness

We used a data set consisting of 154 observations (i.e., 60-cm hoops) to evaluate the relationship between embeddedness measurements made with the hoop method and those made by the visual approach. Based on these data, there was a significant linear relationship between measurements made with the two techniques (simple linear re-

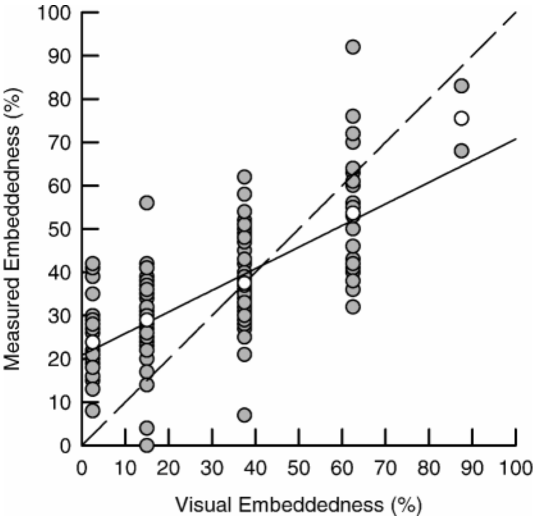

FIGURE 1.—Scatterplot of hoop-measured (measured embeddedness) versus visually estimated (visual embeddedness) cobble embeddedness values. The solid line is the regression model fitted to the complete data set ($F_{1,153}$ = 130.4, $P < 0.0001$, R^2 = 0.46); the dashed 1:1 line is provided for reference. Gray circles represent individual observations, and white circles denote the mean hoop value for the given level of visual embeddedness (mean regression results: $F_{1,4}$ = 97.9, $P < 0.002$, R^2 = 0.97).

gression: $F_{1,153}$ = 130.4, $P < 0.0001$), with the resulting regression explaining nearly half of the variation in hoop-measured embeddedness values (R^2 = 0.46; Figure 1). However, there were differences in the absolute embeddedness value obtained with each method; that is, the regression clearly deviated from the 1:1 line (i.e., simultaneously, H_0: $\beta_0 = 0$ and $\beta_1 = 1$, $F_{2,152}$ = 88.1, $P < 0.0001$; separately, H_0: $\beta_0 = 0$, $F_{1,152}$ = 175.5, $P < 0.0001$; and H_0: $\beta_1 = 1$, $F_{1,152}$ = 131.8, $P < 0.0001$; parameter estimates appear in Table 1). Specifically, the hoop technique yielded higher values than did the visual approach at low levels of cobble embeddedness, while the reverse was true at high levels (Figure 1).

Percent Surface Fines

As in our cobble embeddedness evaluation, there was a strong association between percent fines estimates obtained by visual and measurement-based techniques. The fitted percent fines regression model was statistically significant ($F_{1,17}$ = 80.1, $P < 0.0001$) and explained the majority of variation in the *y*-variable (i.e., pebble-count-based fines; R^2 = 0.83). The fitted parameters deviated significantly (simultaneously, H_0: $\beta_0 = 0$ and $\beta_1 = 1$, $F_{2,16}$ = 10.89, P = 0.001; parameter estimates appear in Table 1) from expectations based on a hypothesized 1:1 relationship between methods (i.e., both approaches yield the same value for fines at a site). However, separate comparisons of parameter expectations based on a 1:1 relationship demonstrated that the deviation was due primarily to a difference in slope (separately, H_0: $\beta_0 = 0$, $F_{1,16}$ = 2.9, P = 0.109; and H_0: $\beta_1 = 1$, $F_{1,16}$ = 14.1, P = 0.002). Ultimately, it appears that the visual estimation approach yields higher values than the pebble count technique when fine sediments are relatively abundant (Figure 2).

Discussion

Throughout North America, biologists are charged with the task of assessing fish habitat conditions, and for any given attribute there are multiple, potentially different measurement techniques. For substrate variables alone, at least 29 different procedures are used for this purpose (Bain et al. 1999). While the effects of observer variability on measurements made by use of the same method have been considered (Roper and Scarnecchia 1995; Wang et al. 1996; Roper et al. 2002), published evaluations of different measurement techniques for assessing the same variable are few (Wang et al. 1996). For this reason, we evaluated relationships between visual and measurement-based methods.

In our study, we found moderate to strong linear relationships between estimates of percent fines and embeddedness obtained using the visual and

TABLE 1.—Regression parameters and model fit statistics from analyses relating visual and measurement-based estimates of cobble embeddedness and percent surface fines. Results from *F*-tests evaluating simultaneous and separate slope (H_0: $\beta_1 = 1$) and intercept (H_0: $\beta_0 = 0$) hypotheses appear in text (see Results).

Model	Parameter	Estimate (SE)	*t*-statistic[a]	*P*-value[a]	R^2
Embeddedness	Intercept	20.8 (1.6)	13.25	<0.0001	0.46
	Slope	0.50 (0.04)	11.42	<0.0001	
Percent fines	Intercept	6.4 (3.8)	1.70	0.109	0.83
	Slope	0.70 (0.08)	8.95	<0.0001	

[a] Evaluates the null hypothesis that the parameter value is zero.

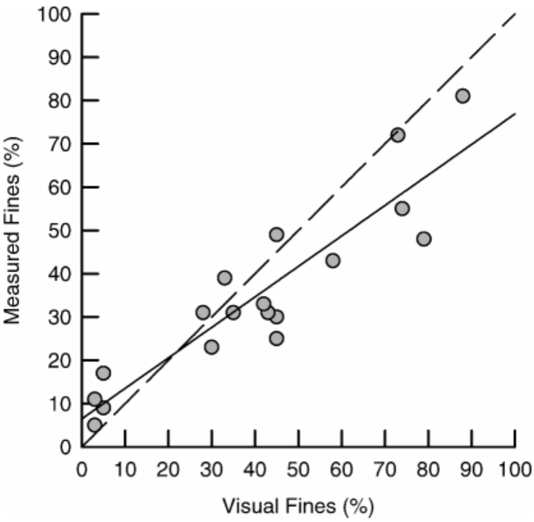

FIGURE 2.—Scatterplot of pebble-count-based (measured fines) versus visually estimated (visual fines) percent surface fine-sediment values (<10 mm). The solid line is the regression model fitted to the data set ($F_{1,17}$ = 80.1, $P < 0.0001$, $R^2 = 0.83$); the dashed 1:1 line is provided for reference.

measurement-based techniques. While these results are in agreement with what has been reported for percent fines methods (Wang et al. 1996; Whitman et al. 2003), they contradict recent suggestions for embeddedness protocols. Specifically, Sylte (2002) and Sylte and Fischenich (2002) concluded that measurements based on visual and hoop embeddedness techniques are weakly and inconsistently associated at best; however, those authors used a different analytical framework for making comparisons (i.e., analysis of variance). In our study, we found visual and measurement-based embeddedness methods to be moderately correlated ($R^2 = 0.46$) when all observations were considered and strongly correlated ($R^2 = 0.97$; Figure 1) when only mean *y*-values (i.e., hoop method averaged at each level of visual embeddedness) were considered in separate regression analyses.

Despite the relationships documented in this study, our evaluation of a 1:1 association between visual and measurement-based techniques indicates that there are differences in the relative bias of approaches. That is, while most methods are biased relative to the unknown, true value of the habitat variable (Bauer and Ralph 2001), visual estimates are typically greater than measurement-based values at relatively high levels of fines or embeddedness. Given the magnitude of deviation documented for embeddedness, we conclude that estimates obtained by means of visual methods are not directly interchangeable (i.e., on a 1:1 basis) with those obtained by the hoop method. In contrast, while there was evidence of deviation between percent fines methods, particularly at high levels of fines, the magnitude of the deviation was minor considering the level of interobserver variability common to these techniques (Wang et al. 1996; Roper et al. 2002). Ultimately, results obtained by visual and measurement-based techniques are comparable for percent fines but not for embeddedness evaluations. The source of deviation between embeddedness techniques, however, requires additional discussion.

While cobble embeddedness can be most generally defined as the ‘‘degree to which fine sediments surround coarse substrates on the surface of a streambed’’ (Sylte and Fischenich 2002), the Platts et al. (1983) visual method and the hoop method (Burns 1984; Skille and King 1989) assess this substrate attribute differently (see Sylte and Fischenich 2002 for a review of embeddedness methods and definitions). In particular, the visual method relies on a surface-only assessment of free cobble area relative to interstitial spaces lost to fine-sediment deposition without any consideration of the vertical or subsurface arrangement of substrate. Hoop embeddedness, conversely, incorporates information on the subsurface arrangement of cobbles and fine sediments; it is quantified as the percent of vertical cobble height embedded into a fine-sediment framework. Thus, investigators estimate embeddedness through visual and measurement-based approaches by means of different but related aspects of information on substrate composition (i.e., surface versus subsurface). This is the most probable reason for the lack of a 1:1 relationship between embeddedness techniques.

Application to Large-scale Habitat Evaluations

While there have been recent institutional efforts aimed at standardizing fish habitat evaluation methods in North America (Bain et al. 1999; Bain and Stevenson 1999; Bauer and Ralph 2001), there is also a wealth of potentially useful nonstandardized information already available for analysis. For example, researchers are currently using preexisting habitat data (based on multiagency, multitechnique surveys) within a life cycle modeling context to assess recovery potential and prioritize restoration efforts for threatened salmon populations (Mobrand et al. 1997; McHugh et al. 2004). Under this approach, variables like percent fines and embeddedness are coupled with published survival–habitat relationships and are used to predict salmon survival and/or productive capacity across several streams. However, without quantitative information on how methods differ, it is uncertain whether model-predicted patterns in restoration potential are procedural or biological in nature.

Studies such as ours that involve quantitative evaluations of the relatedness of different methods for assessing the same habitat attribute provide a means for understanding and accounting for differences among techniques (i.e., by using regression equations to convert between methods). If such an approach is taken, researchers can be more confident that patterns observed across streams, sites, or time periods within large-scale data sets are due mainly to changes in conditions rather than to measurement approaches.

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